

TWO MODELS OF GRAIN TEMPERATURES AND INSECT POPULATIONS IN STORED WHEAT

S. Mani, P. W. Flinn, W. E. Muir, D. S. Jayas, N. D. G. White

ABSTRACT. *Stored grain temperatures and population dynamics of rusty grain beetles, *Cryptolestes ferrugineus* (Stephens), predicted by a hot spot model, which included feedback from the insect model to the temperature model, and a spatial model, which did not include that feedback, were compared. For an initial grain temperature of 30° C and an initial population of 10,000 adult insects in stored grain at Winnipeg, Canada, the hot spot model predicted a maximum of 120 adults/kg of wheat at the center of the grain bulk toward the end of fall and a maximum temperature of 39° C. The spatial model predicted an adult population of 500 adults/kg of wheat and no increases in temperatures. For the same simulation conditions but using weather data for Topeka, Kansas, the hot spot model predicted a maximum of 150 adults/kg of wheat at the center of the bulk in fall, while the spatial model predicted a maximum of 800 adults/kg. The hot spot model is closer to reality than the spatial model because it simulates the effects of variable heating around the bin wall, insect heat production, and insect movement.*

Keywords. *Hot spot model, Spatial model, *Cryptolestes ferrugineus*, Insect population dynamics, Insect migration, Stored grain.*

Stored-grain ecosystems are complex due to the large number of abiotic and biotic factors and their interrelationships. Computer models have been used to simulate abiotic factors, such as temperatures, moisture contents, and gas concentrations, and biotic factors, such as population dynamics of insects and mites, and fungal growth (Jayas, 1995). Most of the heat transfer models, which simulate temperature distributions in stored grain bulks, assume that the effect of internal heat generation on grain temperatures is negligible (Jayas, 1995). Most of the insect and pest management models simulate the effects of homogenous grain temperatures on insect populations and assume no movement of the insects within the grain bulk (Throne, 1995).

Under Canadian storage conditions, the centers of large bins remain warm and favorable for the multiplication of a major stored product pest, rusty grain beetles, *Cryptolestes ferrugineus* (Stephens). Insects tend to move to the warm regions from the cold regions of grain bulks and aggregate at the centers of the bulks (Mani, 1999; Flinn et al., 1992). Temperatures in stored grain bulks vary with time and space

and affect the population dynamics and distributions of insects in stored grain bulks. Only a few attempts have been made to simulate the feedback from heat transfer models to insect models (Longstaff et al., 1981; Flinn et al., 1992; Mani, 1999). Longstaff et al. (1981) incorporated a model of the population dynamics of *Sitophilus oryzae* (Cuff and Hardman, 1980) in a model of heat and moisture transfer in aerated grain (Sutherland et al., 1971).

Flinn et al. (1992, 1997) developed a spatial model that simulates the population of *Cryptolestes ferrugineus* (Stephens) based on non-homogeneous temperatures in stored grain bulks. Mani (1999) simulated insect-induced hot spots in stored wheat. The hot spot model includes the effects of internal heat generation on grain temperatures and the population dynamics of *C. ferrugineus*, as well as the movement of insects based on temperature gradients in the stored grain (Mani, 1999). The main objective of this research was to compare grain temperatures and insect populations predicted by the hot spot model (Mani, 1999; Mani et al., 2001) with those predicted by the spatial model (Flinn et al., 1992) for two climatic regions.

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DIFFERENCES BETWEEN THE HOT SPOT AND SPATIAL MODELS

The differences between the hot spot (Mani, 1999; Mani et al., 2001) and spatial models (Flinn et al., 1992) were:

- (1) The hot spot model uses a three-dimensional, finite-element model of heat transfer, which simulates variable heating around the bin wall (Alagusundaram et al., 1990). The spatial model uses a two-dimensional, fi-

nite difference model to simulate the grain temperatures in a south-facing sector of a cylindrical bin (Flinn et al., 1992).

- (2) A cohort-structured model of the population dynamics of *C. ferrugineus* (Kawamoto et al., 1989) is used in the hot spot model. On the other hand, a distributed-delay model of the population dynamics of *C. ferrugineus* (Flinn et al., 1992) is used in the spatial model. In the cohort-structured model, daily cohorts of the insects move through the life-stages, and a continuous age distribution is simulated. In the distributed-delay model, a delay process is used to move the immature insects through their life-stages and to simulate variations in developmental rates.
- (3) In the hot spot model, adult age is designated as physiological age, which is measured in degree-days (Kawamoto et al., 1989) after emergence of adults. In the spatial model, adult age is stored in a 70-element array, which limits the maximum age of adults to 70 d. In the hot spot model, adult age is dependent on grain temperatures, while in the spatial model adult age is temperature-independent.
- (4) The spatial model does not include feedback from the insect model to the heat transfer model. The hot spot model, however, simulates the effects of insect heat production on grain temperatures and the effects of grain temperatures on insect heat production (Cofie-Agblor et al., 1996a, 1996b).
- (5) In the hot spot model, the movement of adults is determined by the temperature gradients and insect densities in the grain bulk (Mani, 1999; Mani et al., 2001). The spatial model does not include insect movement.

SIMULATION PROCEDURE

Temperature distributions and insect densities in an unaerated, 8.5-m diameter bin filled with wheat to a depth of 6 m were simulated by both the hot spot and spatial models. In the hot spot model, the bin was discretized into 440 linear, three-dimensional elements. The mass of wheat in each element was approximately 600 kg. The 6-m tall bulk was divided into 5 layers, 1.2-m thick. Temperatures were predicted at 109 nodes in each horizontal plane, for a total of 654 nodes for the grain bulk (Mani, 1999; Mani et al., 2001). In the spatial model, a sector of an 8.5-m diameter bin was divided into 16 compartments with 77 nodes (Flinn et al., 1992). In the spatial model, the temperature model feeds the insect model with compartment grain temperatures and moisture contents.

In the hot spot model, insects were introduced into four elements at the 3-m depth and four elements at the 1.8-m depth (Mani, 1999). The location and volume of these elements were equivalent to the center-middle compartment where the insects were introduced in the spatial model. The moisture content of the wheat was assumed to be 14.5% (wet basis). Because of the different harvesting seasons, the starting dates of simulations were 15 July 1986 for Topeka, Kansas, and 01 September 1986 for Winnipeg, Canada.

To compare the two models, four sets of conditions were simulated with both models:

- (1) Adult insect populations were simulated for wheat maintained at constant temperatures of 25°, 30°, 35°, and 40° C for one year. This comparison eliminated the effects of the different heat transfer and heat production components of the two models and compared the different submodels for the population dynamics of *C. ferrugineus*. The initial insect density was set at 0.01 newly emerged adult females/kg of wheat.
- (2) Insect populations and central grain temperatures were simulated for Winnipeg weather when initial conditions were favorable (10,000 adults and 30° C) and were not favorable (20 adults and 25° C) for the development of a hot spot in the bin.
- (3) Insect populations and central grain temperatures were simulated for Topeka weather when initial conditions were the same as those simulated for Winnipeg (10,000 adults and 30° C; 20 adults and 25° C).
- (4) Insect populations and central grain temperatures were simulated for Topeka weather when daily immigration of insects into the bin was included. A daily immigration rate for *C. ferrugineus* has not been measured under Winnipeg storage conditions. Because of the low ambient temperatures during fall, daily immigration of *C. ferrugineus* is probably quite low or negligible. Hence, this comparison was done only for Topeka storage conditions. Daily immigration rates of 0.0014 adult females/kg of wheat in the top layer (0.0 to 1.2 m depth) and 0.00074 adult females/kg of wheat in the other layers (1.2 to 6.0 m depth) were assumed for the storage period from 15 July to 01 October (Flinn et al., 1997). An initial grain temperature of 32° C and moisture content of 12% (wet basis) were assumed for this comparison at Topeka. To determine the effect of immigration, the same storage conditions were simulated for an initial introduction of 10,000 adults at the center of the bulk and no daily immigration.

RESULTS AND DISCUSSION

PREDICTED INSECT POPULATIONS AT CONSTANT TEMPERATURES

The submodels of the population dynamics of *Cryptolestes ferrugineus* (Stephens) in the hot spot and spatial models were compared by simulating the effects of constant grain temperatures on insect population densities (fig. 1). At a constant grain temperature of 25° C, the hot spot model predicted an insect population of 2,200 adults/kg after 360 d of storage, while the spatial model predicted 170 adults/kg (fig. 1). The hot spot model predicted an earlier development of the insect population when the grain temperature was at 30° C. The insect population reached a peak of 3,800 adults/kg, and due to the simulated mortality at the high insect density (Mani, 1999; Mani et al., 2001), the insect population then decreased (fig. 1). At 30° C, the insect population predicted by the spatial model increased to 5,300 adults/kg.

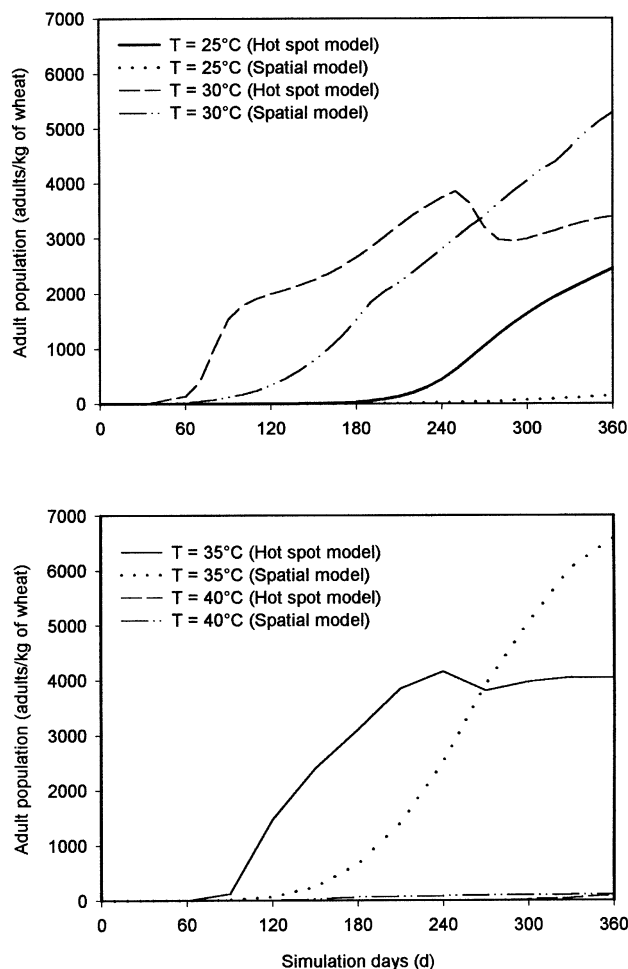


Figure 1. Adult *C. ferrugineus* populations in wheat maintained at constant temperatures predicted by the hot spot and spatial models (initial insect density was 0.01 newly emerged adult females/kg of wheat).

At 35°C, the hot spot model predicted a maximum of 4,000 adults/kg, and the spatial model predicted a maximum of 6,600 adults/kg. At 40°C, which was the maximum temperature predicted in an insect-induced hot spot (Mani, 1999), the hot spot model predicted no development of insects, and the spatial model predicted slow development. For constant temperatures from 30° to 40°C, the insect populations predicted by the hot spot model were lower than those predicted by the spatial model, but at 25°C, the hot spot model predicted higher insect populations than those predicted by the spatial model. These variations were due to the different way the models simulate insect ages.

SIMULATIONS UNDER WINNIPEG STORAGE CONDITIONS

For a low initial population of 20 adult insects and an initial grain temperature of 25°C under Winnipeg storage conditions, the temperatures simulated by the hot spot model with and without insects were the same (fig. 2). Even though the insect population increased over the time period, the heat produced by the insects was not sufficient to increase the grain temperatures. The maximum difference between the center temperature predicted by the spatial model and the hot spot model was 5°C at the end of the simulation period. The

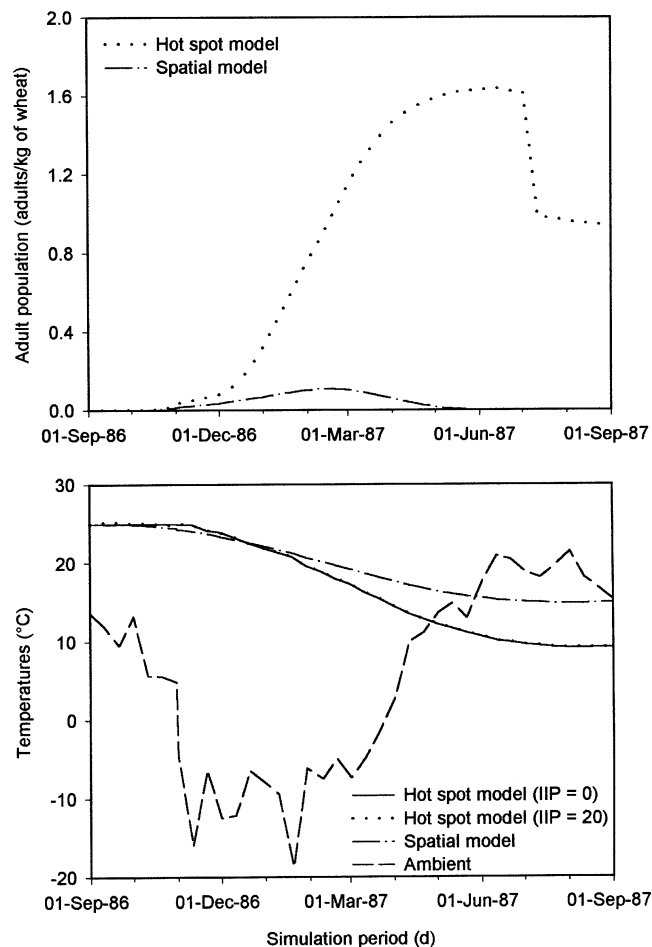


Figure 2. Average temperatures and adult *C. ferrugineus* populations predicted by the hot spot and spatial models at the center of an 8.5-m diameter bin filled with wheat to a depth of 6 m at Winnipeg, Canada, when 20 adults (IIP = initial insect population) were introduced at the center of the wheat bulk on 01 Sept 1986 (initial grain temperature = 25°C, total mass of wheat at the center of the bulk = 5,000 kg). The temperatures with IIP equal to 0 and 20 were nearly identical.

two-dimensional model of heat transfer in the spatial model calculated radiation on the southern 55% of the bin wall. Because the spatial model does not include the variations in solar heating around the bin and predicts the temperatures on only the south side of the bin, the temperatures predicted by the spatial model were higher than those predicted by the hot spot model.

The insect population densities predicted by the spatial model increased until March and then decreased to zero as the temperature at the center of the bin continued to decrease due to thermal lag. The spatial model is based on a development period that rapidly lengthens with decreasing temperatures. Because grain temperatures at the bin center fell below 20°C, reproduction and development of the insects were reduced to near zero. *Cryptolestes ferrugineus* do not develop and multiply at temperatures below 17°C, but they survive (Fields and White, 1997). The model of *C. ferrugineus* in the hot spot model simulates continued slow development and reproduction at low temperatures. Hence, the insect densities predicted by the hot spot model (1.6 adults/kg) were higher than those predicted by the spatial model (0.1 adults/kg),

even though the predicted center temperatures were lower (fig. 2). In summer, because the temperatures of the grain surrounding the center of the bulk increased, the adults migrated from the center of the bulk to the surrounding grain, thereby causing the adult population at the center of the bulk to decrease (fig. 2). The total adult population in the bin, however, did not decrease.

For an initial insect population of 10,000 adults and an initial grain temperature of 30°C, the hot spot model simulated a hot spot at the center of the bulk toward the start of fall (fig. 3). A peak temperature of 39°C was predicted at the center of the bulk at the end of fall when the spatial model predicted 27°C. The hot spot model predicted a maximum insect population of 120 adults/kg at the center of the bulk. Because of the detrimentally high temperature of the hot spot, the model simulated insect migration from the hot spot to the surrounding bulk and decreased the insect population to near zero at the center of the bulk. The total adult population in the bin, however, did not decrease. In the

following summer, due to insect multiplication and warm ambient conditions, the temperatures of the surrounding grain bulk increased and the average temperatures at the center of the bulk also increased.

The temperatures predicted by the spatial model were 10°C below those predicted by the hot spot model (fig. 3). The population density predicted by the spatial model, however, reached a higher maximum of 500 adults/kg. This was because the spatial model predicts rapid multiplication of insects at temperatures greater than 25°C (fig. 1) and no insect movement away from high temperatures and insect densities at the center of the bin.

SIMULATIONS UNDER TOPEKA STORAGE CONDITIONS

For an initial insect population of 20 adults and an initial grain temperature of 25°C, temperatures predicted by the hot spot model were lower than those predicted by the spatial model for Topeka, Kansas (fig. 4). Temperatures predicted by the hot spot model under Topeka weather conditions (fig. 4)

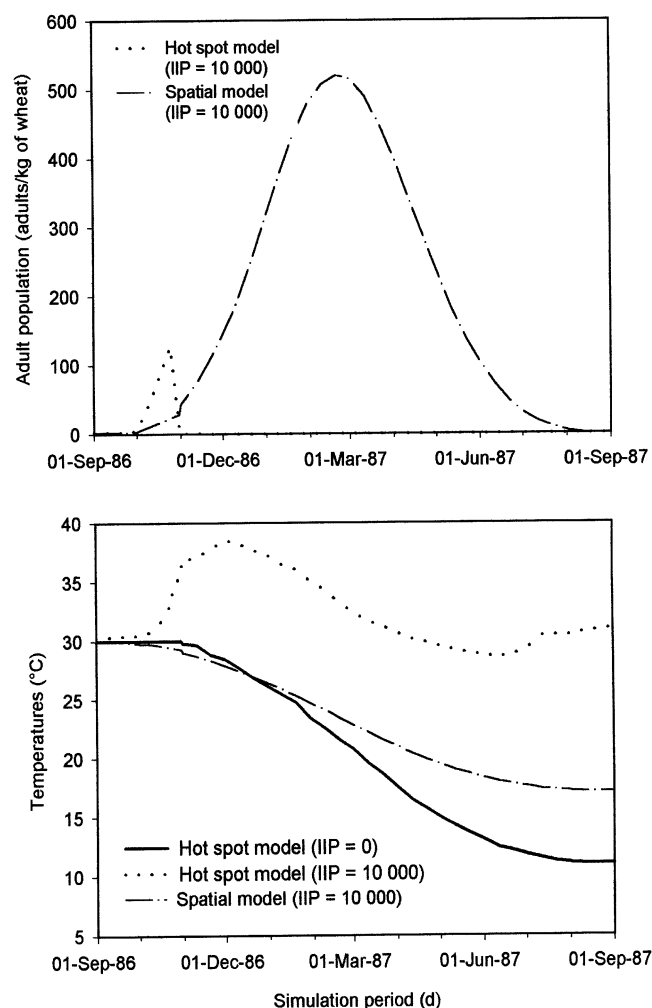


Figure 3. Average temperatures and adult *C. ferrugineus* populations predicted by the hot spot and spatial models at the center of an 8.5-m diameter bin filled with wheat to a depth of 6 m at Winnipeg, Canada, when 10,000 adults (IIP = initial insect population, adults) were introduced at the center of the wheat bulk on 01 Sept 1986 (initial grain temperature = 30°C, total mass of wheat at the center of the wheat bulk = 5,000 kg).

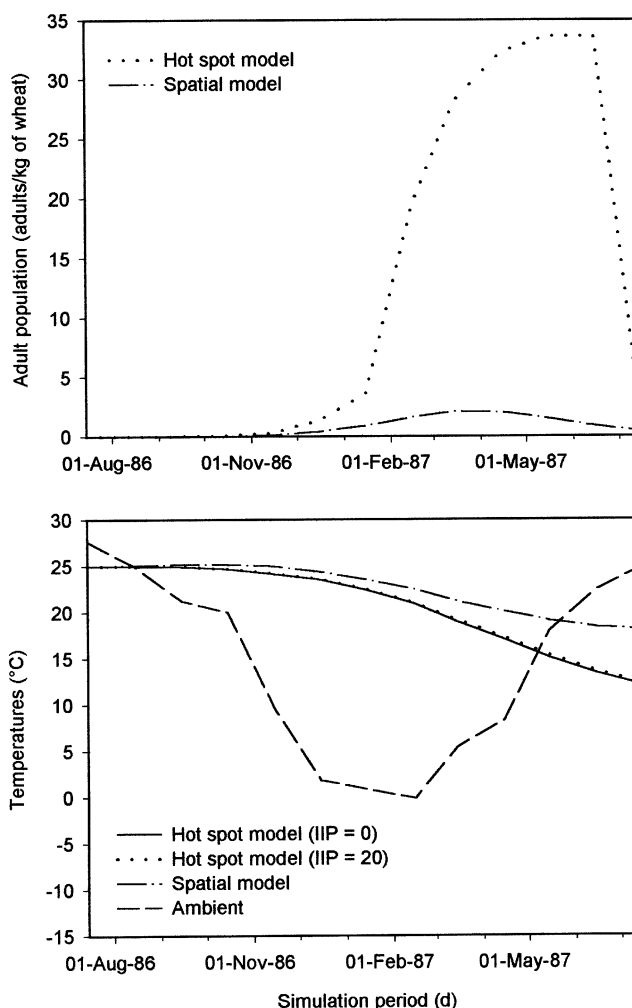


Figure 4. Average temperatures and adult *C. ferrugineus* populations predicted by the hot spot and spatial models at the center of an 8.5-m diameter bin filled with wheat to a depth of 6 m at Topeka, Kansas, when 20 adults (IIP = initial insect population, adults) were introduced at the center of the wheat bulk on 15 July 1986. The temperatures with IIP equal to 0 and 20 were nearly identical.

were higher than those predicted under Winnipeg weather conditions (fig. 2). This was because the grain under Topeka storage conditions was harvested and stored 45 d earlier (15 July) than under Winnipeg storage conditions (01 September), and the ambient temperatures in Topeka were warmer than those in Winnipeg. Hence, initial insect multiplication was high and the population reached a peak of 34 adults/kg under Topeka storage conditions, whereas under Winnipeg storage conditions it reached a peak value of 1.6 adults/kg. Even though the insect population increased rapidly, the heat produced by the insects was insufficient to cause a hot spot in the grain bulk (fig. 4). A maximum population of 1.8 adults/kg was predicted by the spatial model under Topeka storage conditions (fig. 4). Both models predicted maximum populations at Topeka (fig. 4) about 20 times higher than at Winnipeg (fig. 2).

For an initial insect density of 10,000 adults and an initial grain temperature of 30°C, the hot spot model predicted a hot spot in early fall and temperatures remained warm throughout the simulation period (fig. 5). A maximum

population of 150 adults/kg was predicted by the hot spot model, which was only slightly higher than 120 adults/kg for Winnipeg (fig. 3). Under Topeka storage conditions, the spatial model also predicted a higher insect population (a maximum of 800 adults/kg) than under Winnipeg storage conditions (a maximum of 500 adults/kg). During the following summer, due to predicted center temperatures below 25°C, the insect population decreased to 400 adults/kg (fig. 5).

SIMULATIONS BASED ON DAILY IMMIGRATION OF INSECTS

When daily immigration of insects into the grain bin was assumed under Topeka storage conditions (Flinn et al., 1992), hot spots developed in late fall, and the hot spot model predicted warm grain temperatures throughout the simulation period (fig. 6). At the end of the simulation period, the maximum difference between the temperatures predicted by the hot spot and spatial models was 10°C. The hot spot model predicted a maximum of 100 adults/kg by the end of

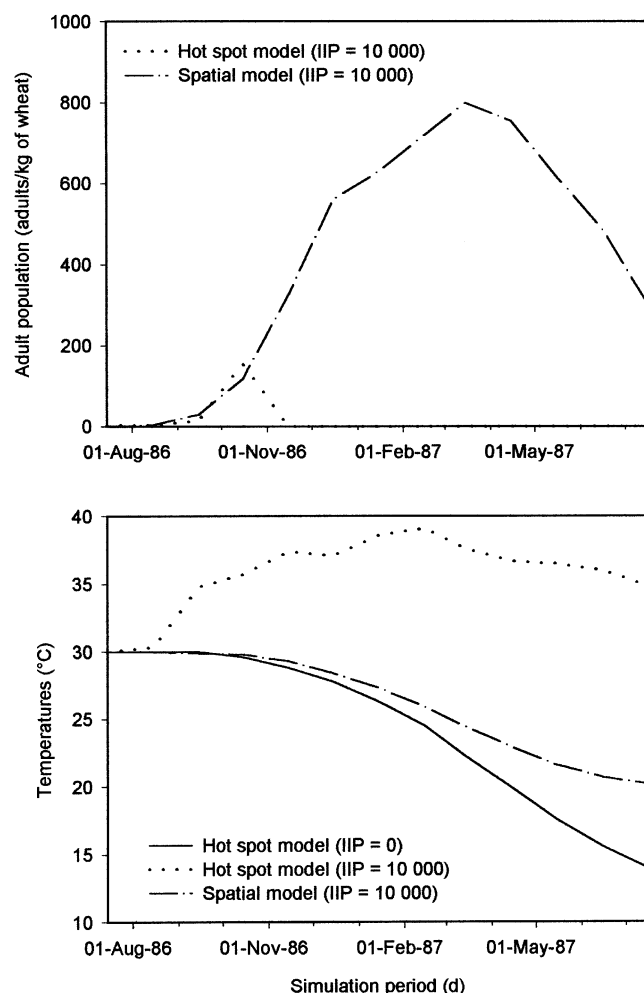


Figure 5. Average temperatures and adult *C. ferrugineus* populations predicted by the hot spot and spatial models at the center of an 8.5-m diameter bin filled with wheat to a depth of 6 m at Topeka, Kansas, when 10,000 adults (IIP = initial insect population, adults) were introduced at the center of the wheat bulk on 15 July 1986.

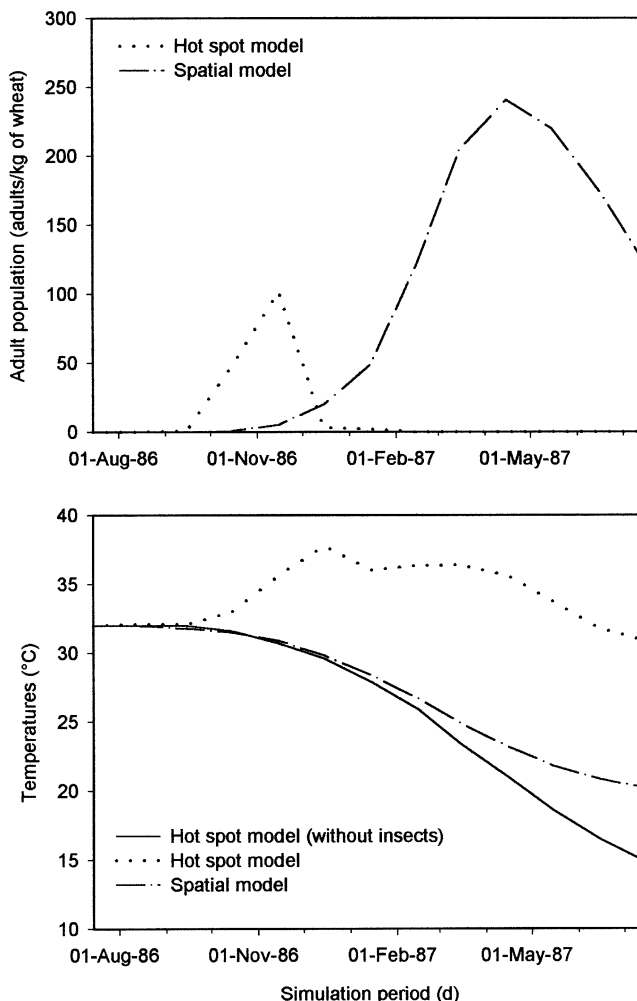


Figure 6. Average temperatures and adult *C. ferrugineus* populations predicted by the hot spot and spatial models at the center of an 8.5-m diameter bin filled with wheat to a depth of 6 m at Topeka, Kansas, and daily immigration rates of 0.0014 adult females/kg of wheat in the top layer (0.0 to 1.2 m depth) and 0.00074 adult females/kg of wheat in the other layers (1.2 to 6.0 m depth) from 15 July to 01 October.

fall and then, due to the simulated migration of insects from the high temperatures and insect densities, insect population at the center decreased to near zero (fig. 6). The spatial model predicted a maximum of 250 adults/kg at the center of the bulk in the following spring. These variations in the maximum population were due to the inherent differences between the hot spot and spatial models. Due to the low grain temperatures and no immigration of insects, insect populations decreased during the following summer.

For the spatial model, the maximum population predicted based on daily immigration of insects (fig. 6) was 3.2 times lower than the maximum population predicted, for the same simulation conditions, when 10,000 adults were introduced initially at the center of the bulk with no daily immigration (data not shown). Daily immigration causes slow initial development of the insects in the center-middle compartment and no movement of insects between compartments. For the hot spot model, the maximum population predicted based on a daily immigration of insects (fig. 6) was the same as the maximum population predicted, for the same simulation conditions, when 10,000 adults were introduced initially at the center of the bulk with no daily immigration (data not shown). The maximum population based on daily immigration of insects, however, was attained 75 d later than when insects were introduced initially. This was because of the time taken by the immigrant insects to move to and aggregate at the center of the grain bulk.

CONCLUSIONS

Under Winnipeg storage conditions, with an initial grain temperature of 30°C and an initial insect population of 10,000 adults (2 adults/kg), the insect density at the center predicted by the hot spot model reached a maximum of 120 adults/kg near the end of fall and center temperatures reached a peak of 39°C. The spatial model, however, predicted a maximum adult population of 500 adults/kg and no increase in grain temperatures. For the same simulation conditions, under Topeka storage conditions, the hot spot model predicted a maximum of 150 adults/kg by early fall, while the spatial model predicted a maximum of 800 adults/kg. Due to the warmer weather conditions and earlier storage of grain in Topeka, the predicted insect population was higher and the hot spots occurred earlier than those predicted under Winnipeg storage conditions. When simulating daily immigration of insects under Topeka storage conditions, the insect population predicted by the spatial model (250 adults/kg) was higher than that predicted by the hot spot model (100 adults/kg). The wide divergence between some of the results predicted by the two models indicates a need for more data and submodels on insect movement and mortality due to temperature gradients and other factors. This research is now being conducted (Jian et al., 2000)

The hot spot model is an improvement over the spatial model because it simulates the effects of variable heating around the bin wall, insect heat production, and insect movement. Although some components of the hot spot model have been validated or were based on substantive

experimental data, the overall model has not been tested. The spatial model was validated with data from a 350 m³ bin in Kansas (Flinn et al., 1992).

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